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Richard A. Elliott

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The experimental data were analyzed by N. J. McCormick of the University of Washington under a companion project Determination of Optical Properties by Inversion of Multiple Scattering Data: Analytic Program. It was shown that it is possible to estimate the single scatter albedo of weakly absorbing particles with a relative error of less than 1%.

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DETERMINATION OF OPTICAL PROPERTIES BY INVERSION OF MULTIPLE SCATTERING DATA: EXPERIMENTAL PROGRAM

Final Report

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Richard. A. Elliott

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Oregon Graduate Center

19600 N. W. Von Neumann Drive

Beaverton, OR 97006-1999

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An experimental study designed to test the effectiveness of a time dependent inverse radiative transfer algorithm for determining the single scatter properties of optically thick media is described. The inversion algorithm required measurements of the time resolved backscattered radiance following ultrafast pulsed illumination of model, optically thick, atmospheres. Most of the measurements were accomplished with 532 nm, 35 ps duration pulses from a frequency doubled, passively mode locked Nd:YAG laser and a 10 ps resolution streak camera. The last series of measurements were made with a synchroscan streak camera and 5 ps duration pulses from a dye laser synchronously pumped with an acoustooptically modelocked Argon ion laser.

The experimental data were analyzed by N. J. McCormick of the University of Washington under a companion project *Determination of Optical Properties by Inversion of Multiple Scattering Data: Analytic Program.* It was shown that it is possible to estimate the single scatter albedo of weakly absorbing particles with a relative error of less than 1%. Estimates of the asymmetry factor were found to be unreliable when particle diameters were much less than the wavelength of the scattered light but relative errors of only a few percent were achieved when particle diameters were comparable to or larger than the wavelength.

DETERMINATION OF OPTICAL PROPERTIES BY INVERSION OF MULTIPLE SCATTERING DATA: EXPERIMENTAL PROGRAM

INTRODUCTION

The operation of optical systems in the low visibility atmosphere of the modern battlefield is a matter of great concern. Laser ranging, tracking, target designation and communication systems are all severely impacted by the aerosols and dust endemic to the battlefield environment. Laser pulse shapes can be grossly distorted and beam diameters and pulse durations increased by orders of magnitude by multiple scattering [1,2]. Since smokes and artificial fogs can therefore be simple countermeasures to such laser systems it is important not only to understand the optical effects of aerosols but, from the point of view of negating these countermeasures, to be able to determine the composition and optical properties of the battlefield atmosphere by remote measurement.

There has been considerable effort expended on developing remote sensing methods but most of this work relies on the target being optically thin and neglects multiple scattering effects. However, a recent reformulation of the inverse scattering problem, which developed an inversion algorithm utilizing both angle and time resolved measurements of backscattered radiation following pulsed illumination, may provide a way to extract single scatter information from optically thick, multiple scattering, atmospheres [3 - 7]. The algorithm extracts the coefficients of the Legendre polynomial expansion of the single scatter phase function from backscattered radiance data. The first coefficient in the expansion is the single scatter albedo and the second is directly related to the asymmetry factor. The goal of the experimental study described here was to obtain data on well characterized model scattering systems with which to test the efficacy of the inversion algorithm.

EXPERIMENTAL

The inversion algorithm requires time resolved measurement of the backscattered radiance at a polar angle θ and azimuthal angles, ϕ_j, $j = 0,1,...J$, following illumination of the surface of the scattering medium with a pulsed, collimated beam at a polar angle, θ_0. The geometry of the scattering problem is illustrated in Figure 1 and a schematic layout of the experiment designed to make these measurements is shown in Figure 2. A frequency doubled, passively modelocked Nd:YAG laser was used to produce 532 nm light pulses of approximately 35 ps duration and 50 μJ energy. A $\lambda/4$ wave plate converted the linearly polarized laser beam to circular polarization and lenses L1 and L2 expanded the beam to 3.1 cm diameter (e^{-1} intensity) before it was directed at an angle θ_0, with respect to the normal to the antireflection coated entrance window of the scattering cell. Mirrors M1 and M2, the aperture, and lens L3 collected the light scattered in the direction (θ, ϕ) and directed it to the streak camera. Beam

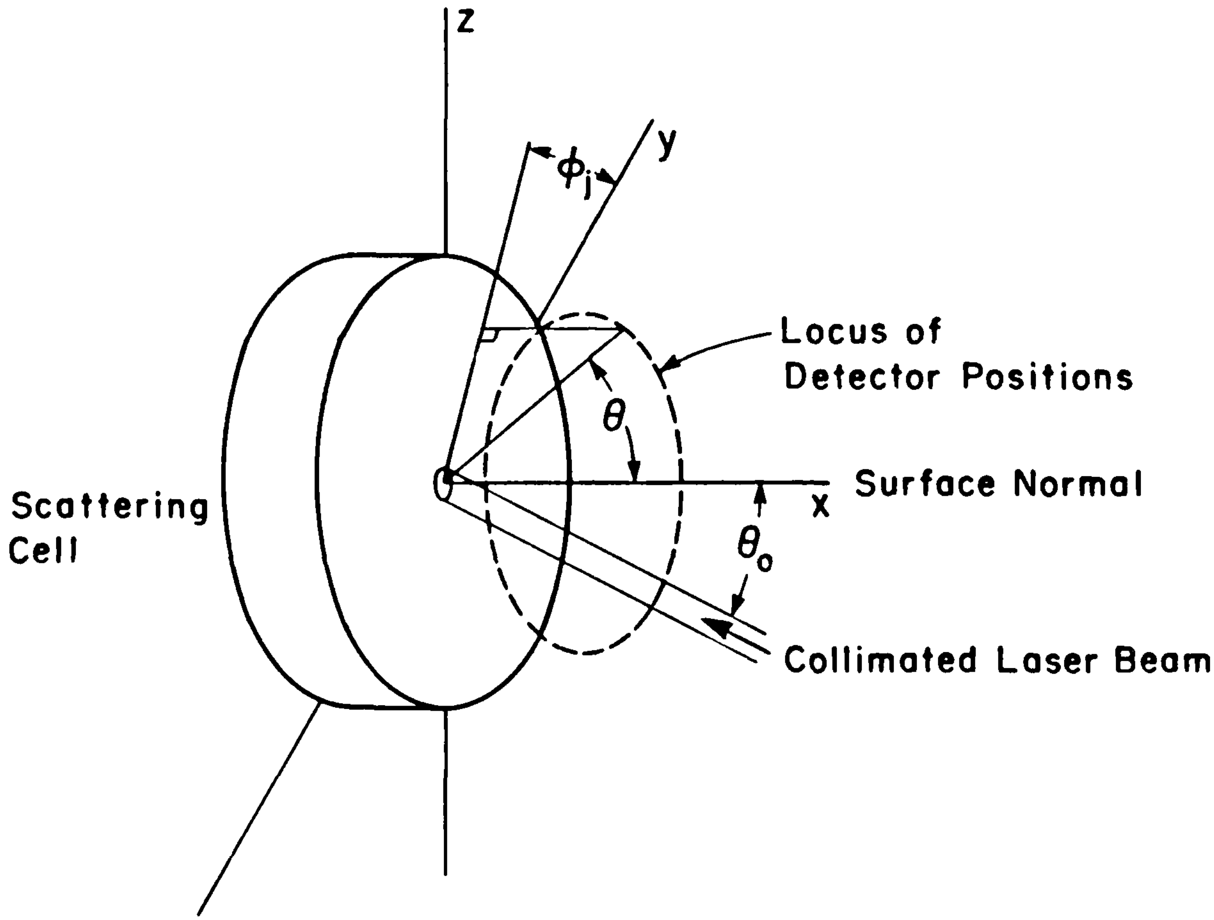

Figure 1. Geometry of backscattered radiance measurements. The collimated laser pulse is incident on the scattering cell at a polar angle θ_0. The streak camera detects light backscattered at a polar angle θ and azimuthal angle ϕ.

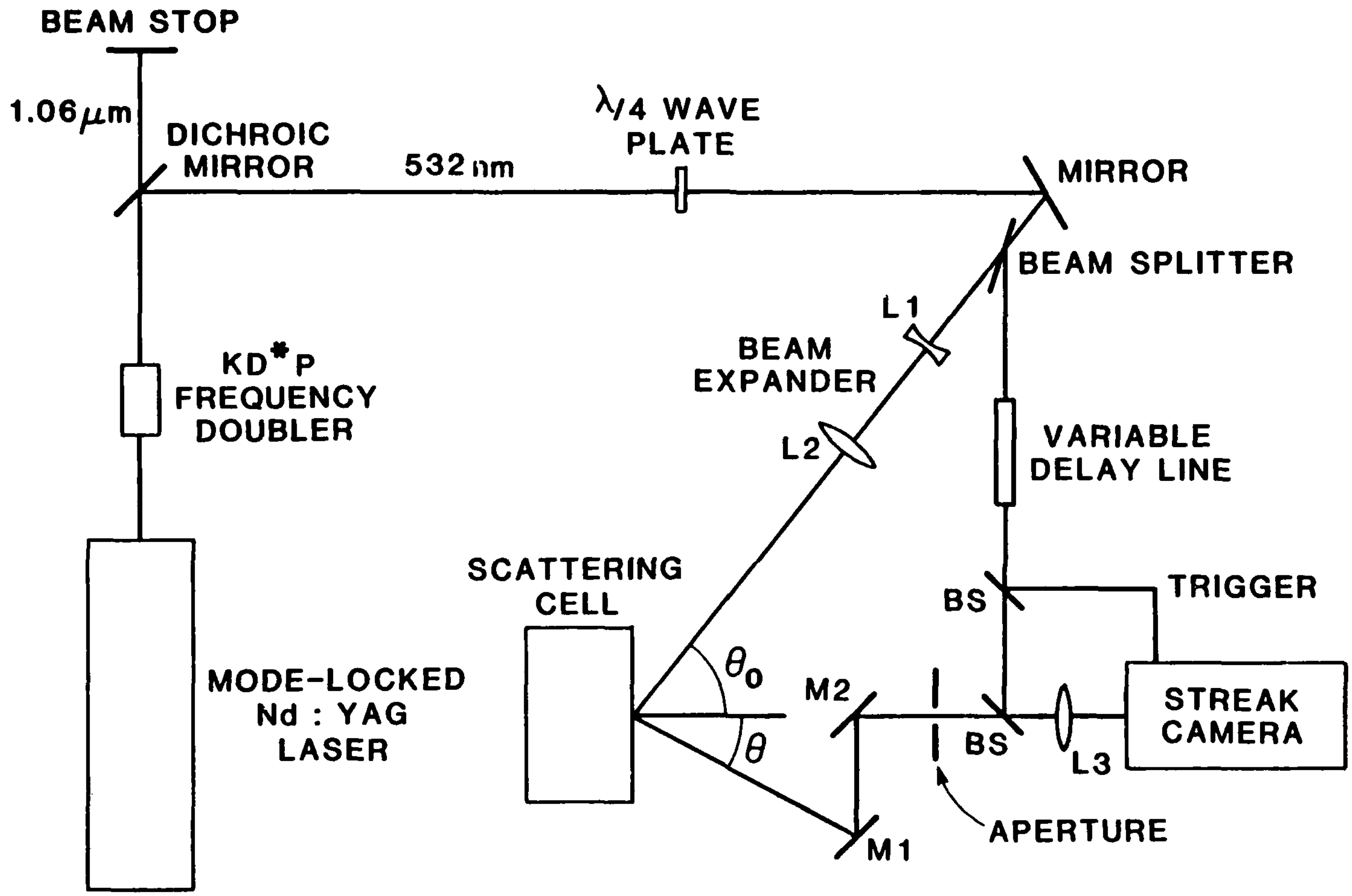

Figure 2. Schematic of the experimental layout.

splitters and a variable delay line were used to trigger the streak camera and to provide a reference light pulse needed for precise time registration and amplitude normalization. Figure 3 is a typical example of an intensity-versus-time record constructed from the digitized data provided by the streak camera. The record shows the reference pulse, which is a replica of the incident pulse, on the left and the backscattered radiance on the right. The unit of time is a channel, i.e., the streak camera sampling interval, which for this record is 4.31 ps.

The scattering experiments were performed on aqueous suspensions of nonabsorbing polystyrene latex spheres of diameters 91 and 482 nm, and on weakly absorbing polymer *Dynospheres* of diameter 1900 nm. Typically twenty individual measurements of the backscattered radiance such as that shown in Figure 3 were recorded for each angular position. Measurements were made at three different polar angles, 15°, 21°, and 28°, and at least at 7 azimuthal angles; as many as 24 azimuthal angles were used in some cases. The raw data and the twenty pulse averages were recorded on floppy disks and forwarded to N. J. McCormick at the University of Washington for analysis under the companion project *Determination of Optical Properties by Inversion of Multiple Scattering Data: Analytic Program.* The inversion of the backscattered radiance data to obtain the first few coefficients of the Legendre polynomial expansion of the single scatter phase function was accomplished with his recently developed algorithm.

In the last six months of the program some of the experiments were repeated using a dye laser synchronously pumped with an acoustooptically modelocked Argon ion laser as the pulse source and a newly acquired synchroscan streak camera. The dye laser provided 5 ps duration pulses at a repetition rate of 76 MHz. The high prf and synchroscan streak camera made a great improvement in the SNR of the data and reduced the time needed to perform an experiment by a large margin. Unfortunately this better quality data was acquired so late in the project that insufficient time remained to complete its analysis. The analysis and inversion of this data will be completed as resources permit.

RESULTS

The following table compares experimentally derived values of the single scatter albedo and the asymmetry factor with those calculated by means of Mie scattering theory. These data were obtained from a single set of experiments performed with the 35 ps duration pulsed Nd:YAG laser system. A more detailed exposition of the inversion algorithm and further experimental results have been published (see Publications section below).

It may be noted that the single scatter albedo was in all cases estimated to within less than 1% relative error. Similar results were obtained for the asymmetry factor on the largest, 1900 nm diameter, spheres but there was a relative error of 5% in the asymmetry factor for the 482 nm diameter spheres and no reliable estimate could be obtained for the smallest, 91 nm diameter, spheres. From this it can be concluded that

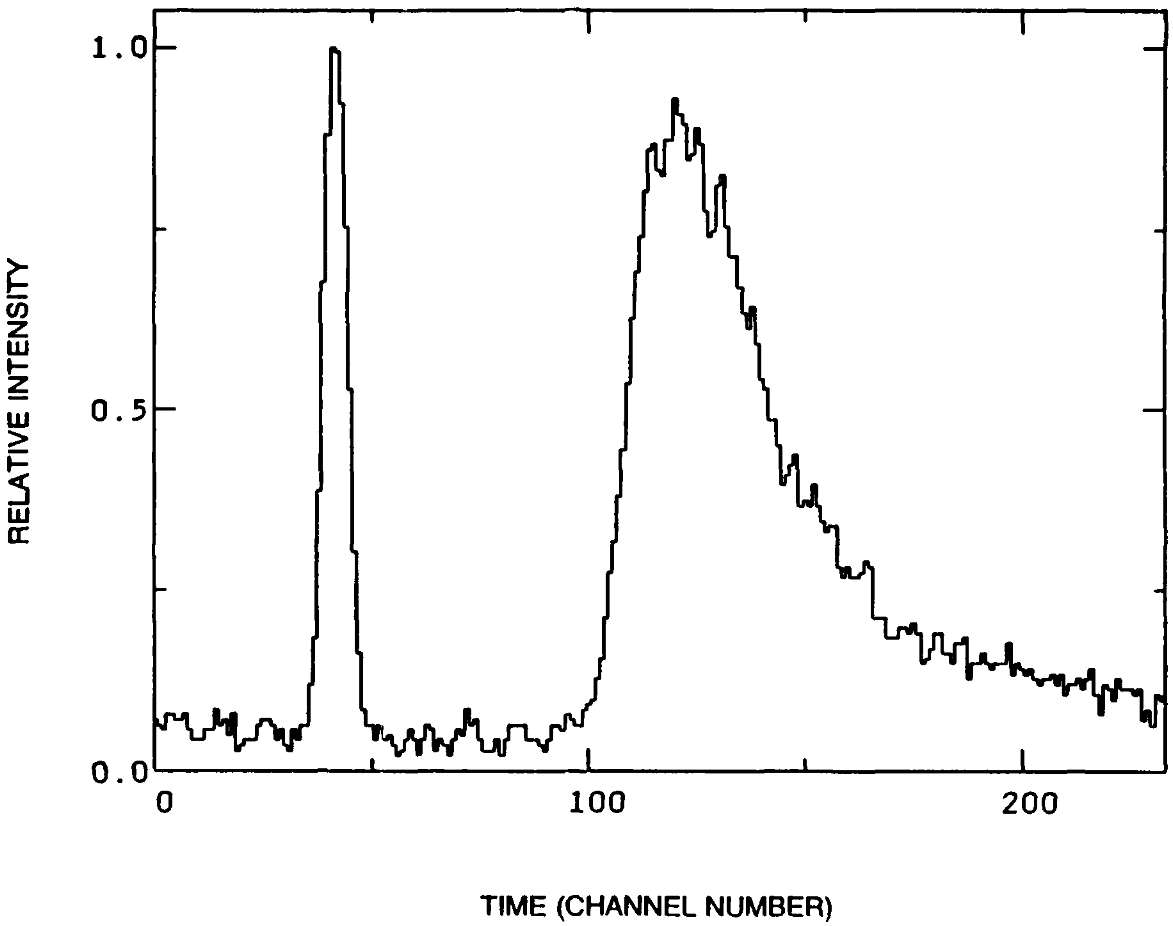

Figure 3. Typical streak camera record of the reference pulse and backscattered radiance.

it is possible to use time resolved backscattered radiance measurements and the inversion algorithm developed by McCormick to estimate the albedo of single scattering to better than 1%. The asymmetry factor can be estimated with reasonable accuracy (<5% error) for spheres with diameters comparable to or greater than the wavelength of the probing light pulse. It is unlikely that higher order coefficients can be obtained with this method.

Table I

Sphere Diameter (nm)	Coefficient	Mie Theory	Experiment
91	Albedo Asym.	1.0000 0.0889	1.0025 -
482	Albedo Asym.	1.0000 0.8497	0.9991 0.8923
1900	Albedo Asym.	0.9993 0.8964	0.9976 0.9002

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2. R. A. Elliott, "Multiple scattering of optical pulses in particulate media," Proceedings of Symposium on Multiple Scattering of Waves in Random Media and Random Rough Surfaces, Pennsylvania State University, July 29 - August 2, 1985.
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LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

Richard A. Elliott, Principal Investigator.
Richard K. DeFreez, Student, Ph.D. 1985, Faculty Associate.
Donald R. Emmons, Student, Ph.D. 1986.
Lisa A. Sargent, Student.
Benjamin Taylor, Student.
David Bossert, Student.

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